Development of the Mariner C Solar Panel Deployment System at Jet Propulsion Laboratory* (A)

In April 1962, the Jet Propulsion Laboratory (JPL) completed the preliminary design of a spacecraft known as Mariner B. NASA planned to send the Mariner B to Mars in 1964 using a Centaur boost vehicle. Soon after JPL began detailed design work on the spacecraft, difficulties arose with the Centaur. NASA then asked JPL to investigate the feasibility of building a spacecraft which an Agena D could boost. A study showed that this was possible and JPL was told to proceed on the program. Mars would come within shooting range of the Agena D during November 1964, and would not be within range again for another 25 months. JPL would have to deliver three assembled spacecraft to Cape Kennedy in September 1964. There would be less than 2 1/2 years in which to develop the Mariner C. Since the Agena D had only about 1/2 the thrust of the Centaur, the new spacecraft (to be called Mariner C) would be severely weight constrained.

*The efforts described in this case study represent the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

Prepared in the Design Division of the Department of Mechanical Engineering by Sue Hays under the direction of Professor H. O. Fuchs with financial support from the National Science Foundation. This is a condensation of a case history written by engineering students R. Kerr, R. Weitzmann, and C. Yokomizo at the University of California at Berkeley under the supervision of Professor R. F. Steidel, Jr.

JPL, which is operated by the California Institute of Technology under a NASA contract, develops unmanned spacecraft to aid in increasing scientific knowledge of lunar and interplanetary space. The Laboratory has seven technical divisions: Systems, Space Science, Telecommunications, Guidance and Control, Engineering Mechanics, Engineering (test) Facilities, and Propulsion. In addition, each major project has its own organization. (Exhibit A-1 shows part of the organization for the Mariner C project.) At the time NASA asked JPL to consider developing the Mariner C, previous JPL projects had included the Explorer program, which produced the first United States satellite, the Pioneer program, the Mariner II program, and the Ranger program, which resulted in a rough landing attempt on the moon. A Ranger program to photograph the lunar surface would proceed simultaneously with and have priority over the Mariner C project. This would complicate the scheduling of test facilities for the Mariner C.

The conceptual design of a spacecraft requires interaction between people representing many technical disciplines and interests. At JPL, such efforts are coordinated by a Spacecraft System Project Engineer. The man assigned to head up the conceptual design on Mariner C was Mr. John Casani. The Mariner C design team adapted a unique approach for defining the mission in greater detail. Every morning, a list of tasks for Mariner C to perform on its mission would be outlined. During the day the team would discuss such aspects of the proposed mission as feasibility, power, and weight limitations. A new mission would then be outlined for consideration the next day.

Detailed study was limited to a "fly-by" mission; that is, to a mission which would orbit the spacecraft relatively close to Mars. This type of mission was thought to be quite likely to succeed and to yield more desirable data than missions which would place the spacecraft on an impact course with Mars or place it in a very large orbit about Mars. Originally, the design team constrained itself to working with modifications of spacecraft such as Mariner II and Ranger. Such an

approach is an economical one if the desired performance can be obtained. However, after a week of considering various fly-by requirements, it became apparent to the design team that more than simple modifications would be required to meet the stringent weight limitations.

The Mariner C Project Engineer for the Spacecraft Development Section of the Engineering Mechanics Division was Mr. James Wilson. This Division had responsibility for spacecraft structures, mechanisms, temperature control, electronic packaging and cabling, a large part of the configurational design, ground handling equipment, and mechanical design support to other JPL technical divisions. After a week of preliminary design effort, Mr. Wilson told Mr. Casani that he felt that 50 lbs. of weight could be saved by going to a fresh configuration rather than attempting to retain Mariner II and Ranger structural concepts. Mr. Casani gave Mr. Wilson the go-ahead on a Friday afternoon, and Mr. Wilson's section spent most of the week-end looking at new configurations. Quick layouts and weight calculations verified the estimated weight savings. The system weight could be reduced to a value within the capability of the Atlas Agena D by using some rather radical structural approaches.

Because of decreased solar intensity in the vicinity of Mars solar power sources for Mars spacecraft assume increasing importance from a weight standpoint. During the early phases of the Mariner C study, nuclear power was considered. However, because of the problems of nuclear integration, the relatively small amount of power required, and successful experience with solar power, the design team decided quite early to use solar panels on the Mariner C. Mr. Wilson's section was responsible for the design of the geometrical configuration and structure of the solar panels. The electrical aspects of the solar panel design and fabrication were the responsibility of the Guidance & Control Division. The engineers involved took into consideration the performance of solar panels on previous spacecraft as well as advances in the state of the art. They decided to use four 3 foot by 6 foot rectangular panels. Attitude control jets would be mounted on the tips of the panels rather than on the body of the spacecraft. Since the jets would have

greater moment arms, the required jet force would be less, and fifteen pounds of spacecraft weight would be saved.

As detailed design of the Mariner C progressed, the design began to "gain weight"; most spacecraft designs do. When the first weight crises arose in late 1962, Mr. William Layman, an engineer in the Engineering Mechanics Division, had an idea about a way to reduce weight. He estimated that the weight of the solar panels could be halved if point damped supports were used to control their fundamental resonance during the initial boost. Mr. Layman had developed a sliding concentric tube damper (see Exhibit A-2) to reduce the resonance displacements of an antenna on the Mariner II. Layman had later suggested that the damper be used to support the solar panels on the Ranger spacecraft. Although vibration tests verified that the dampers would reduce panel vibration, problems arose in developing the sliding tube dampers, and they had not been flown on the Ranger.

The structural engineers were the chief objectors to the idea of using damped solar panels on the Mariner C. They argued that their analytic capabilities were limited to lightly damped structures with linear characteristics. Layman's proposal involved heavy, nonlinear damping. Furthermore, no previous spacecraft system had had its success contingent upon the successful operation of dampers. Their use involved some risk and appeared to violate Mariner C project guidelines.

Mr. Layman, however, was able to convince Mr. Wilson that the solar panels should be damped. The two of them convinced Section Chief William Schimandle. Because Mr. Schimandle was also Project Manager for the Division, he was able to override the protests of the structural engineers. When the use of damped solar panels was recommended to the Project Office, the Office decided to accept the risk irvolved. In December 1962, the Office modified the proposed plan for the solar panel system to include the use of dampers.

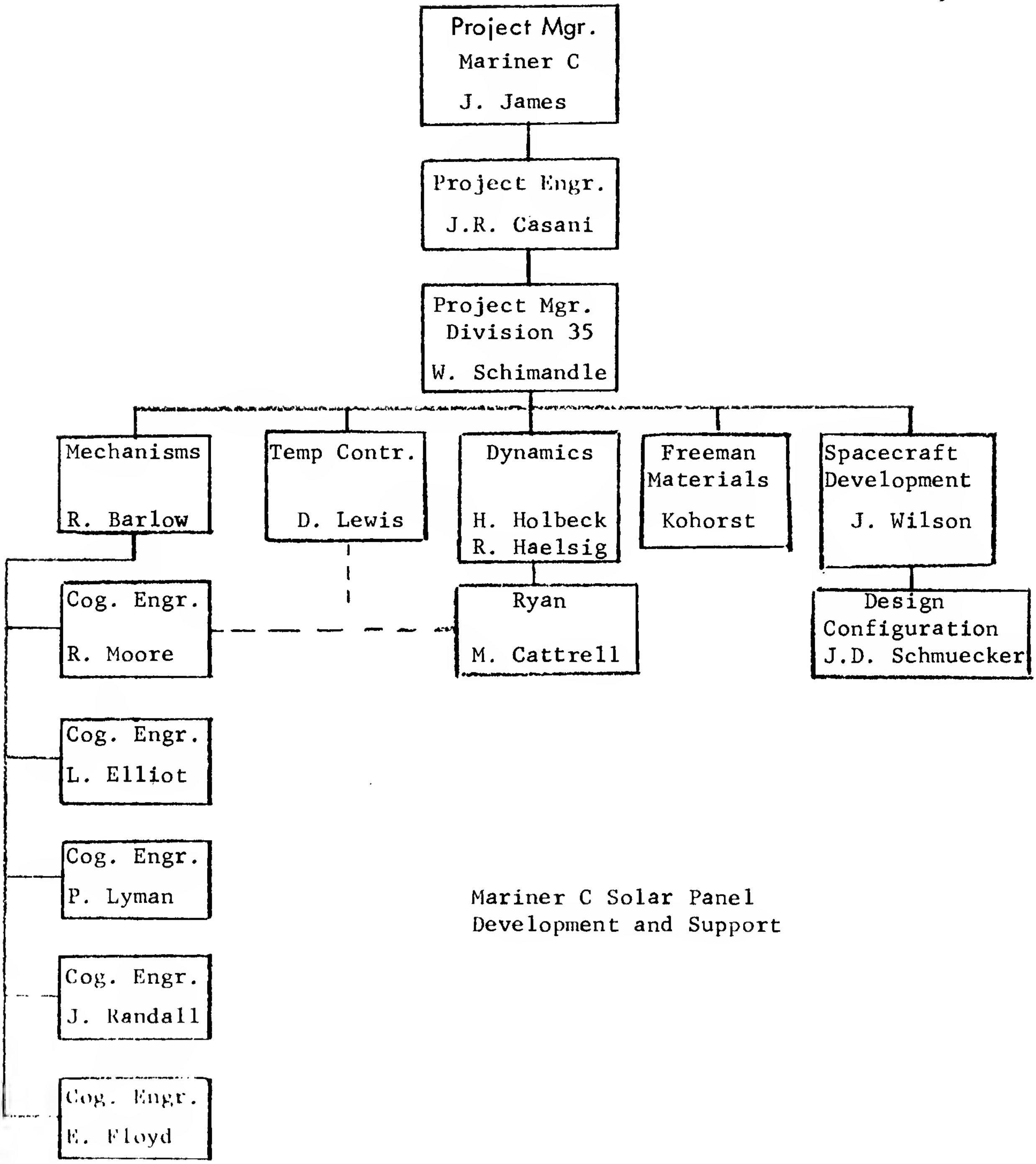
The spacecraft would be an octagonal structure with four damped solar panels extending from the structure to form a cross. Radio antennas would be located above the octagon. Optical equipment for taking television pictures of Mars and for tracking Canopus, the reference star, would be located below the octagon. The spacecraft would be about 9 1/2 feet in height, 5 feet in diameter and about 22 1/2 feet from panel tip to panel tip. See Exhibits A-3 and A-4 for photographs.

LIST OF EXHIBITS

Development of the Mariner C Solar Panel Deployment System

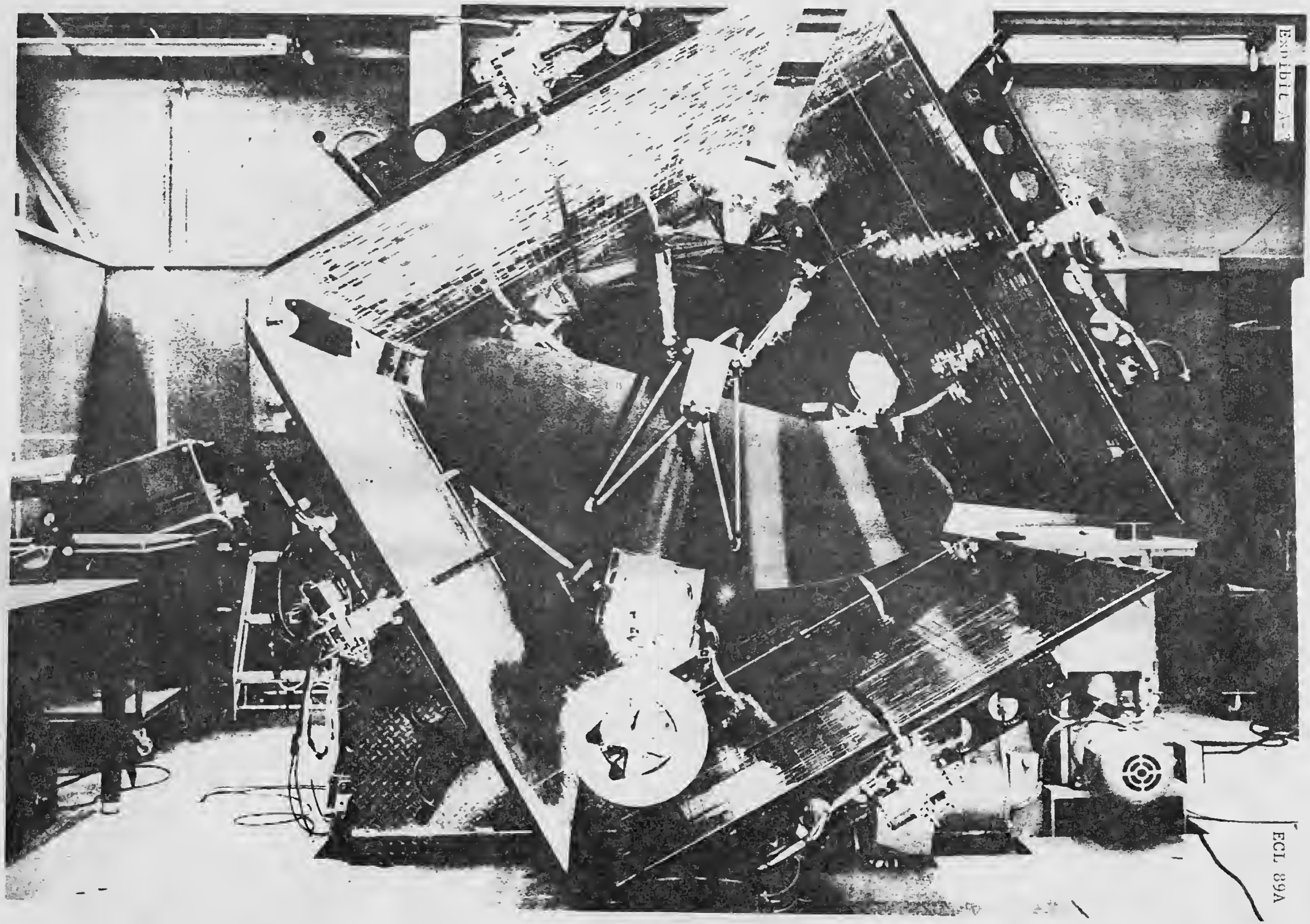
Jet Propulsion Laboratory

Part A

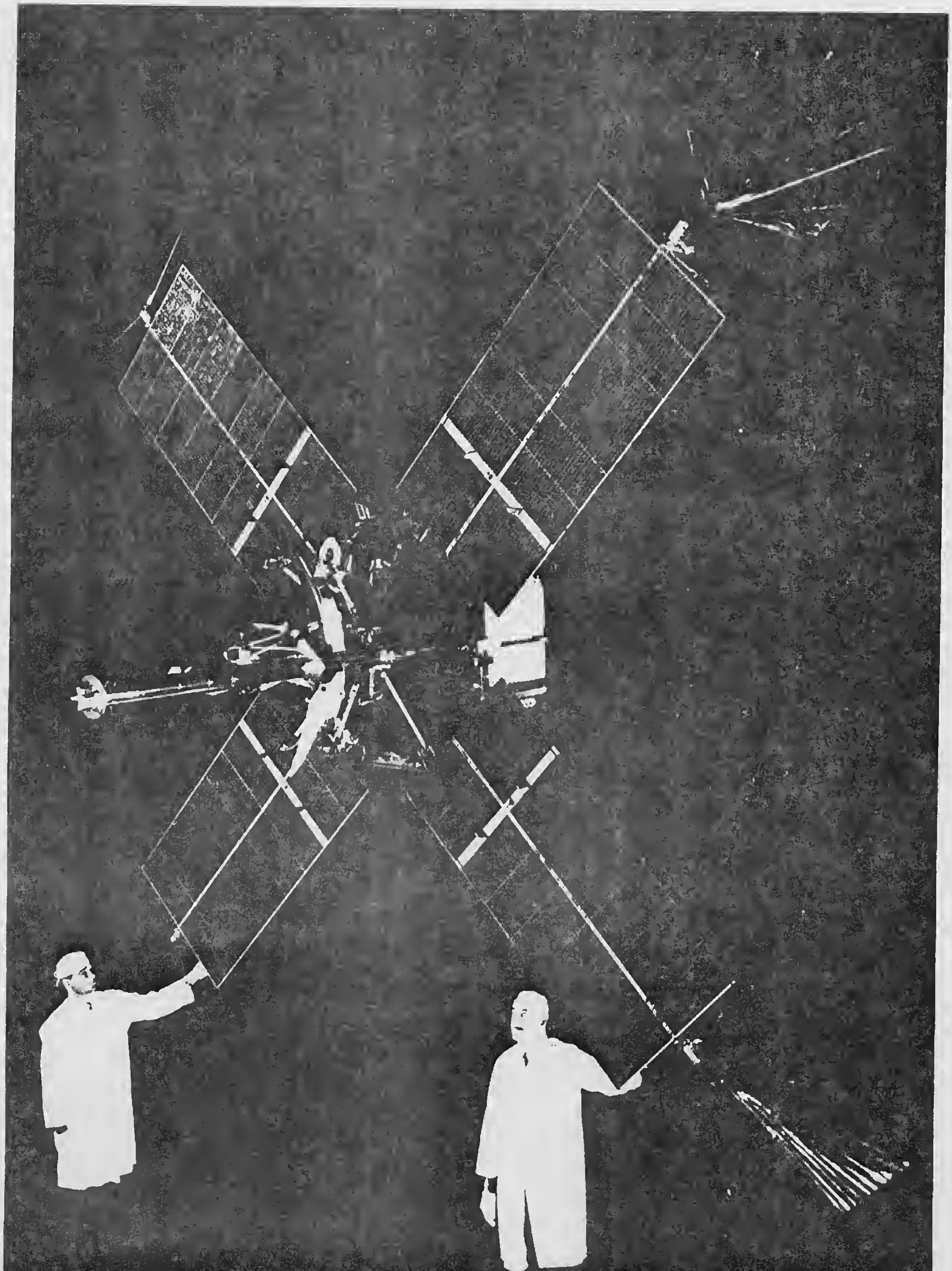


Mariner C Solar Panel
Development and Support

Mariner C Sliding Concentric Tube Damper



Mariner C Spacecraft Folded



Mariner C Spacecraft With Solar Panels Deployed

Development of The Mariner C Solar Panel Deployment System At Jet Propulsion Laboratory (B)

It was crucial to the success of the Mariner C mission that the solar panels deploy properly and that they not be damaged. Not only did the panels provide the main source of power for the spacecraft, but also the attitude control jets would be mounted to the tips of the panels. Unless all four panels deployed satisfactorily, it would be impossible to stabilize the spacecraft properly. Mechanisms such as those used to deploy solar panels are the proverbial nail in the horseshoe. If they fail the entire mission may be lost. In the case of Mariner C, the penalty would have been $125,000,000 and two years delay in the exploration of Mars. As a result, development of spacecraft mechanisms is never taken lightly. However, mechanism design and development is a very tricky business. No matter how conceptually simple, performance is seldom completely predictable.

The panel deployment system used by JPL on the Ranger and Mariner II had worked satisfactorily, and JPL engineers originally intended to use the same system, with a few minor changes in hardware, on the Mariner C. This deployment system was a set of hydraulically damped linear actuators -- one for each solar panel. Each actuator consisted of a compression spring supplying force to a push rod with silicone oil as the damping fluid.

In addition to the damped actuators used for deployment, the solar panels would need "boost dampers" and "cruise dampers". Two boost dampers would hold each solar panel in a vertical position on top of Mariner's octagonal base structure during the boost. These dampers would protect the delicate panels from excessive vibration. When the panels reached their full deployment positions, they would latch onto cruise dampers which would keep the panels from "flapping" during the mid-course maneuver.

As development of the Mariner C system progressed, many engineers began to worry about using the existing linear solar panel actuators. They were afraid that the silicone oil in the actuators might leak during the long flight (eight months) and contaminate the temperature control surfaces and the optical instruments. In addition, the engineers discovered that they would have to extend the stroke of the actuators to adapt them to the Mariner C. This meant adding an additional linkage to each actuator thereby increasing weight.

During the development of the Mariner II, an earlier JPL spacecraft, Mr. Richard Moore of Mr. Schimandle's section had tried to think of alternate ways of deploying the solar panels. One concept which occurred to him was to use a torsion bar actuator to supply the deployment torque and a centrifugal friction brake to damp the panel motion. Each torsion bar and each friction brake would have one end mounted to a solar panel and the other to the octagonal base structure. A planetary gear box would multiply the panel velocity, in order to produce a centrifugal force which would cause friction pads in the brake to contact a brake lining. This friction damping would hold the deployment velocity constant.

This scheme seemed potentially advantageous because of its rotary operation. Mr. Moore was therefore told to design such an actuator to be used on the Mariner C.

In January 1963, Mr. Moore became Cognizant Engineer for the entire panel system. At that time the status of the deployment system was indicated by the following definition:

> Four panels 3 by 6 feet, hinged at one end to the octagonal base structure of the spacecraft, are to be deployed simultaneously at a controlled rate through approximately 90°. Deployment shall be completed within 45 seconds after the panels are released from the boost dampers by explosive squib pin pullers. The initial design of the torsion bar actuator is to be continued and, once developed, shall be used to deploy the panels.

> Dynamic coupling between the panels and the base structure shall be provided by means of a damper for each panel to specifications which will be given by the Dynamics Group. Contact between the panel and the damper shall be established by latching the deploying panel to the damper.

For the most part, the deployment performance requirements (45 seconds) were based on experience with previous spacecraft. As Mr. Barlow, Mr. Moore's group leader, said, "This is the way we had always done it, earlier missions had successfully been flown with these specifications under similar panel configurations. After a program has begun, it is almost always too late to try something which has never been done before. There are too many risks involved with radically new concepts, and these risks are difficult to accept on a limited time basis."

Soon after Mr. Barlow made Mr. Moore Cognizant Engineer, he offered an engineering position to Mr. Elliot. Mr. Elliot had recently graduated from college with a degree in Mechanical Engineering and had been working at JPL on the Ranger program for about a year. Barlow gave Elliot some of the jobs Moore had had before he became Cognizant Engineer. Mr. Elliot now became responsible for the solar panel deployment system.

By March 1963 a prototype of the torsion bar actuator had been made, and Mr. Elliot began testing it. The actuator is shown in Exhibit B-1. These actuators were rather heavy -- four of them weighed a total of 4.5 pounds. As is usually the case with newly developed mechanisms, several problems occurred in test. The planetary gear drive was improperly designed so that actuation torque was inadequate. The high stress level in the torsion bar caused unacceptable plastic deformation. The design obviously required additional development and was nowhere near as satisfying in hardware form as it had been in concept. At this stage there was one year remaining before the completed spacecraft was to begin final flight acceptance testing. The hardware freeze date was rapidly approaching. Quite a bit of design and development effort had been invested in the torsional

actuator. However, since more effort was required, Mr. Elliot and Mr. Moore decided to consider the deployment problem anew.

After some thought, Mr. Elliot suggested that the torsional actuators be abandoned. He suggested that the panels be individually spring loaded as before, but that all of them be retarded by one central retarder. He hoped his idea would increase the reliability of the system and decrease its weight. The central retarder which he proposed would be attached by cables to each of the panels and would allow them to open simultaneously in about 45 seconds. The retarder assembly itself would be a hydraulic vane torque brake which would damp motion by forcing fluid from one side of a vane to the other through a tapered orifice. Mr. Elliot had tried to minimize the possibility of fluid leakage in his design. Furthermore, he wanted to use alcohol instead of silicone oil as the damping fluid because alcohol, should it leak out, would not leave a film on the optical lenses.

In late June 1963, Mr. Elliot presented his central retarder idea to a Design Review Board which consisted of certain JPL engineering staff members. The only difficulty Elliot foresaw with his idea was that air bubbles might form in the liquid as the retarder was filled. Air bubbles would prevent smooth retardation of the panels. In general, the Design Review Board liked the central retarder idea. The Board members agreed that the new design would be lighter, cheaper, and more reliable than the torsion bar actuator design. The total weight of the new system would be 3.5 pounds -- one pound less than the weight of the torsion bar system. The Board decided that the filling of the retarder could be done in a vacuum to prevent formation of air bubbles. The Board members could not agree as to whether alcohol or silicone oil should be used, however. One group of members wanted to pursue the alcohol idea. Silicone oil could be used if trouble developed, they claimed. The other members argued that all development time should be spent on the oil system. They pointed out that the actuator parts would be better lubricated and better

damped. Eventually, the Board decided to try using alcohol as the damping fluid. This decided, the Board examined the mechanics of the retarder, the connecting cables, and the deployment springs. A total of sixteen recommendations were made on the recommended design. These recommendations ranged from the use of better seals to the generation of test plans to uncover any additional problems which might develop.

Mr. Barlow and Mr. Wilson decided to do a complete failure mode analysis of the central retarder concept. The purpose of the analysis would be to examine critically the failure possibilities in the system, to assess the impact these failures would have on the spacecraft, and to recommend corrective measures. Exhibit B-3 is a summary of the failure mode analysis which Mr. Barlow and Mr. Wilson conducted.

The Design Review Board met again in August 1963 to discuss the failure analysis. The Board felt that the most serious, and most probable failure mode would be unretarded motion of a solar panel. (This is referred to in the summary as "free fall" although the panels are deployed by springs, not by gravity.)

At this meeting, the Board was less impressed by the central retarder design. An excerpt from a summary of the Board's views says:

> The general consensus of the Board was that the current design left a bad taste in its mouth. Whether these feelings are the result of poor engineering or poor aesthetics may never be ascertained. At any rate, the feeling was that the basic system should be reexamined, simplified, cleaned up aesthetically, thoroughly tested, and thrown away.

The Board made several specific recommendations which included the following:

1. Latch cables to panel after panel is folded up. This should minimize the possibility of cable snarling.

2. Check case of panel free fall to determine if panel is damaged.

3. Look for alternative deployment approaches (one likely contender is to let the panels free fall, stopping them with the damper which is to provide the dynamic coupling and a piece of balsa wood to absorb excess energy.

Since June, Mr. Elliot had been following the recommendations made in the first Review Board meeting. Tests made on prototype models demonstrated that using alcohol would require extremely tight fits and tolerances. He therefore had to discard the alcohol idea and return to silicone oil. Other tests revealed other difficulties with the central retarder. Oil leakage was still a problem. The temperature compensation scheme was inadequate. There were also difficulties with the negator leaf springs which were to be used to deploy the panels.

In January 1964, Mr. Elliot left JPL. The Mariner C time schedule dictated that the complete spacecraft enter the space simulation chamber for a flight acceptance test in July 1964 -- six months remained in which to complete the panel deployment system. Considering the short time left before testing was to begin, Mr. Barlow was now faced not only with a very tight time schedule in which to ready the deployment system, but also with the task of redistributing the workload of the central retarder development. The problem had become a crisis. The hiring and training of a new staff member would have required many months and was obviously not feasible at this time. As a result, he reassigned the deployment system as an additional responsibility to other members of his group. The central retarder was given to Mr. E. Floyd for further work and the deployment springs to Mr. J. Randall.

Mr. Floyd, a mechanical engineer on Mr. Barlow's staff who had been with JPL for some years, was Cognizant Engineer on the Mariner C scan actuator drive. He had a large amount of experience in solving unexpected design

problems. Mr. J. Randall was Cognizant Engineer for the solar vane system which was part of the attitude control subsystem.

Mr. Floyd continued to carry out the various recommendations of the Design Review Board. Working on an overtime basis, he gradually developed a workable unit. Mr. Randall decided to work with clock springs rather than the negator leaf springs Mr. Elliot had used because there was a better established technology for clock springs.

In March 1964, tests were begun on the revised central retarder deployment system together with the cruise dampers and latches which had been developed. The retarder is shown in Exhibit B-2. The purpose of these tests was to observe the entire solar panel release, opening, and latching sequence. Tests were conducted by positioning the spacecraft on its "side". The two panels with vertical hinge axes were then released and allowed to move to the latched position. When the tests were carried out, the panels stopped short of latching onto the cruise dampers. After some analysis, the engineers came to the conclusion that each of the deployment system components was performing to its requirements, but that the component requirements were inconsistent. Another result of the tests was that the panels were not damaged when they were allowed to deploy unretarded in air. The deployment time was 5 1/2 seconds, and the cruise dampers and latches were considerably overloaded, but without any serious effects.

Encouraged by the test results, Mr. Barlow decided to further investigate the possibility of letting the panels deploy unretarded. He knew that the terminal velocity of the panels in space would be considerably greater than that in air, but if this free-fall scheme worked, it would increase the reliability of the system and decrease its weight. Mr. Barlow assigned the detailed investigation of the idea to Dr. P. Lyman who up to now had been engaged in the development of the cruise damper. The general approach was to calculate the capacity

of the solar panel, all of its associated hardware and the octagon structure to survive the opening shock. This would yield the allowable deceleration rate. The cruise dampers would then be redesigned to provide the desirable deceleration characteristics, and a test program would be conducted to verify the approach. After a high confidence had been achieved a final test would be run in a vacuum chamber using all flight type equipment. In addition, Mr. Barlow established the following ground rules to be followed in the free-fall development program:

1. Each solar panel shall have two deployment springs, each of which is capable of accomplishing panel deployment.

2. All hardware must be capable of handling the load imposed with both deployment springs operating at the maximum specified torque.

3. There shall be no changes in the solar panel with the possible exception of an extra bolted-on doubler in the latch area. It must be remembered that the panel will be fully equipped with solar cells in place at the time this modification is made (if it is made).

4. There shall be no changes to the electronic chasis or its mounting with the exception of longer bolts for installation of the cruise damper.

5. If at all possible, the damping factor and the spring rate of the cruise damper, when acting as a cruise damper shall not be changed.

Meanwhile, Mr. Floyd and Mr. Randall worked on the latching problem revealed by the tests. In order to get the panels to latch to the cruise dampers, they increased the deployment torque on the panels by increasing the number of deployment springs used. This, along with other features added to solve various problems, increased the weight and complexity of the central retarder system. One member of the Design Review Board compared the central retarder with the original linear actuators used on the Ranger/Mariner II and came to the conclusion

that the linear actuator scheme was slightly better than the central retarder design.

In April 1964, Randall and Floyd finished their revisions on the central retarder system and began testing a prototype. The tests revealed no serious difficulties or additional problems, so they initiated the fabrication of flight hardware.

After completing a dynamic analysis of free-fall deployment, Dr. Lyman decided that the free-fall approach was feasible. Exhibit B-4 shows his analysis. During the months of April and early May of 1964, Dr. Lyman continued to investigate the required changes necessary to use the available Mark I cruise damper with the free-fall system. The changes allowed at this late date had been specified by Mr. Barlow and have been listed above. The mandatory change was to provide sufficient stroke, i.e., energy dissipation, to the damper so that it would not "bottom-out" thus preventing shock loads from being transmitted into the bus or the solar panel. The biggest question that had to be answered was whether or not the spacecraft midcourse firing damping requirements were compatible with the retardation requirements for panel deployment. The energy which must be removed from the moving solar panels is just the change in potential energy of the panel deploy springs. The maximum stroke of the damper was limited by geometrical interface constraints between the solar panel and the bus. The spring rate of the damper springs was determined by the panel frequency requirements. With these parameters defined, or at least bounded, the analysis of the panel deploy dynamics mentioned earlier was performed with the gratifying result that the system requirements were not completely inconsistent. To implement the system, it was necessary to ask the spacecraft System Engineer for a change in the panel damping requirements from a damping ratio of 0.6 to 1.0 matched to five per cent, to a ratio of 0.15 to 0.70 matched to within ten per cent which was, indeed, compatible with the spacecraft autopilot control. (Exhibit B-5 shows the installed cruise damper about to be latched to the solar panel.)

In May 1964, the Design Review Board met to discuss the progress of the free-fall concept. The members agreed that this concept complied with essentially all the original ground rules for the project. The net weight saved would be 2.41 pounds. The Board outlined an extensive and tightly scheduled testing program which included vacuum chamber tests. At this time, the central retarder was already a working system and flight hardware was being manufactured. However, the most probable failure mode of the central retarder was still the free-fall mode. The central retarder system was still called "primary" because another system could not be chosen until it had been proved.

According to the Design Review Board, a final comparison of the central retarder system with the free-fall system revealed:

1. With the free-fall system, far fewer failure modes exist. As a matter of fact, it was not possible to conceive of a single failure mode, assuming that the pin pullers would release the panels, where the free-fall system could abort the mission. With the retarder, there were such failure modes.

2. Reliability of the free-fall system is inherently greater.

3. A source of oil contamination due to the central retarder is eliminated by using the free-fall system.

4. Use of the free-fall system would reduce the spacecraft weight by 2.4 pounds.

5. The decision to utilize the free-fall system is reversible. In fact, should the vacuum deployment test result in surprise damage to the solar panels or structure, the retarder and four spring actuators could be reinstated without reinstating the old cruise damper. Thus the improved damper with its added ability to prevent many retarder failure modes could be used in any event.

In June 1964, the Design Review Board recommended that the free-fall system be made "primary" and made an Engineering Change Request. The central retarder would be the back-up system. Tests of the free-fall system revealed no further problems, and witnesses to these tests described them as "rather dull to

watch."

The first launch of the Mariner C on November 5, 1964 was a failure because of a launch vehicle shroud separation problem. The second launch, in November of 1964, was successful and the spacecraft (now designated Mariner IV) performed almost perfectly. It passed within 6120 miles of the Martian surface on July 15, 1965. It returned 325.5 million bits of scientific data including photographs such as that shown in Exhibit B-6. The spacecraft functioned normally until December 1967 at which time it expended its supply of attitude control gas.

LIST OF EXHIBITS

Development of the Mariner C Solar Panel and its Deployment System at Jet Propulsion Laboratory

Part B

Torsion Bar Actuator

Central Retarder

Cog. Engineer L. Elliott

Division 35 Subsystem Failure Mode Analysis Review

Assembly Part	Description	Description of Assumed Failure	Item Failure Mode	Influence on Mission	Possibility Factor	Possible Methods to Eliminate Failure Mode
Retarder	Empty	Little or no retard force	Panels open very fast - break on impact	Probable failure if panels break completely	1	1. Proper assembly and filling
	Air bubbles	Uneven retardation at higher air % No effect at very low %	1. Possible panel damage 2. Strap(s) break-panel uncontrolled	Failure if panels break-up	Probability is inversely to % air	1. Proper filling technique 2. Leak observation 3. Actuation check
	Foreign Particles	1. Seize up of unit 2. Partial orifice clogging	Dependent on particle size (30 micron estimated critical point.) 2. Slower opening time	No problem unless total seize-up	3 to 10 mic 1 over 10 mic	1. Filter Fluid to 5 microns 2. Clean room assembly 3. Clean filling equipment 4. Assembly, actuate, disassemble and clean, reassemble
	Broken rewind spring	1. Cables slack, retarder opens partially to panel deployed position	1. Panels move rapidly until slack takes up	1. Possible panel damage - depends on amount free travel	1	1. Spring is low stressed 2. Proper tension on cables at button-up
	Kinked strap	Bind up (dependent on location of kink)	One panel either stops completely or slows up temporarily, then catches up - rapidly	1. Partially open panel is failure 2. Slow down and catch up is like air bubbles	2	1. Proper installation and care in assembly 2. Visual check during panel installation and button-up

Cog. Engineer L. Elliott

Division 35 Subsystem Failure Mode Analysis Review

Assembly Part	Description	Description of Assumed Failure	Item Failure Mode	Influence on Mission	Possibility Factor	Possible Methods to Eliminate Failure Mode
	Twisted Strap	Extra friction if twisted area is in pulley or guides	Slows opening of all panels	None	3	Visual inspection
	Notched or nicked strap	Stress concentration	Strap may break allowing one cable to free fall	Free falling panel will probably break up	3	1. Visual inspection 2. Proof load of each strap
	Improper strap adjustment	Slack in one or more straps	Panels "jump" to take up slack	None	1	1.Proper installation and adjustment during panel installation
	Strap out of pulley groove between guards	Probably nothing, but in severe case, loop could form causing kink and jamming retarder	Nothing unless jam up, then panels don't open	Failure if panels do not open, otherwise, none	1	1. Proper installation and adjustment of cables during panel installation 2. Visual inspection
	Retarder temp. outside expected limits	Cold—slows down; Hot—speeds up	Nothing	None	1	1. Preflight calculations and tests
	Thermal gradient	Would take about 400° F gradient across retarder to cause binding	None	None	0 - in order of magnitude to cause failure	1. Retarder was designed to avoid this problem

Cog. Engineer L. Elliott

Division 35 Subsystem Failure Mode Analysis Review

Assembly Part	Description	Description of Assumed Failure	Item Failure Mode	Influence on Mission	Possibility Factor	Possible Methods to Eliminate Failure Mode
One panel does not release with others	1. Panel does not release at all	1. Panel stays folded	1. Low power A/C fouled up	1. Failure	1. 2	Pray
	2. Panel releases later	2. Panel comes down uncontrolled	2. Panel breaks up on impact	2. Failure	2. 1	
Power Spring	One spring breaks	Total torque on retarder is lower than normal	Panels all come down, but slower	None	1	1. Design has two springs per panel Either spring will open panel but at reduced rate 2. Design is such that broken springs ends curl inward with no other damage

Title: PANEL DEPLOYMENT SYSTEM

Prepared by: R.T. Harling Date: 4/24/64

Checked by: Date:

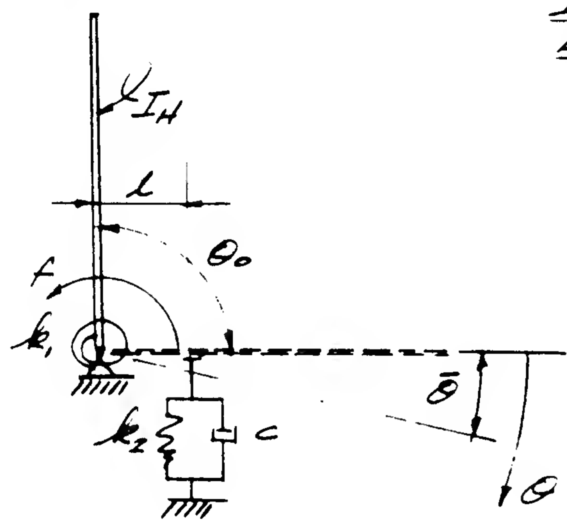
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

Report No. ST 5.03.04 Page

Project: MARINER C

Classification: UNCLASS.

PROBLEM IDEALIZATION



IN THIS SKETCH THE FOLLOWING ABBREVIATIONS ARE EMPLOYED:

I_H = ROTARY INERTIA OF PANEL ABOUT THE HINGE, IN-LB-SEC^2.

k_1 = TORSIONAL ACTUATOR SPRING RATE

f = CONSTANT TORQUE FRICTION

θ_o = ANGLE BETWEEN PANEL BOOST POSITION AND CRUISE LATCH POSITION

l = MOMENT ARM FOR CRUISE DAMPER.

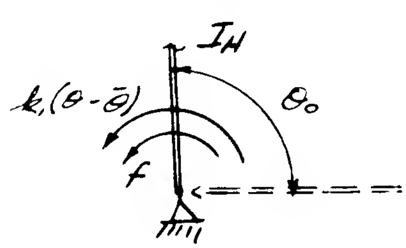
$\bar{\theta}$ = ANGULAR PRELOAD ON ACTUATOR

k_2 = CRUISE DAMPER SPRING RATE

c = " " DAMPING COEFFICIENT

θ = ANGULAR COORDINATE

PRIOR TO ENGAGEMENT OF THE CRUISE DAMPER, THE BELOW FREE BODY DIAGRAM IS APPLICABLE:



$$I_H \ddot{\theta} = -f - k_1(\theta - \bar{\theta})$$

$$I_H \dot{\theta}\frac{d\dot{\theta}}{d\theta} = (k_1\bar{\theta} - f) - k_1\theta; \text{ LET: } q = (k_1\bar{\theta} - f)$$

$$I_H \int_0^{\dot{\theta}_o} \dot{\theta}\, d\dot{\theta} = \int_{-\theta_o}^{0} \left[q - k_1\theta \right] d\theta$$

$$\frac{I_H \dot{\theta}_o^2}{2} = \left[q\theta - \frac{k_1\theta^2}{2} \right]_{-\theta_o}^{0}$$

$$\dot{\theta}_o^2 = \left[q\theta_o + \frac{k_1\theta_o^2}{2} \right]\left(\frac{2}{I_H}\right)$$

$$\boxed{\dot{\theta}_o = \left[\frac{2q\theta_o + k_1\theta_o^2}{I_H} \right]^{1/2}} \quad \text{Eq (1)}$$

Eq (1) EXPRESSES THE VELOCITY AT PANEL-TO-CRUISE DAMPER ENGAGEMENT.

JPL 0899-1-S MAR 63

Title BASIC EQUATIONS
Prepared by R.T. Hailey Date 4/24/64
Checked by ______ Date ______

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

Report No. 35 50304 Page
Project MARINER C
Classification UNCLASS.

FOLLOWING ENGAGEMENT WITH THE CRUISE DAMPER, THE DIFFERENTIAL EQUATION BECOMES:

$$I_H \ddot{\theta} = -f - k_1(\theta - \bar{\theta}) - k_2 l^2 \theta - c l^2 \dot{\theta}$$

$$= \underbrace{(k_1\bar{\theta} - f)}_{g} - \theta(k_1 + k_2 l^2) - c l^2 \dot{\theta}$$

$$\ddot{\theta} + \frac{c l^2}{I_H}\dot{\theta} + \frac{(k_1 + k_2 l^2)}{I_H}\theta = \frac{g}{I_H}$$

TAKING THE LAPLACE TRANSFORM OF THIS D.E.:

$$s^2 F(s) - s(0) - \dot{\theta}_0 + \frac{c l^2}{I_H} s F(s) - \frac{c l^2}{I_H}(0)$$

$$+ \frac{(k_1 + k_2 l^2)}{I_H} F(s) = \frac{g}{I_H s}$$

$$\left[s^2 + \left(\frac{c l^2}{I_H}\right)s + \frac{(k_1 + k_2 l^2)}{I_H}\right] F(s) = \frac{g}{I_H s} + \dot{\theta}_0$$

FACTORING THE TERMS IN THE SQUARE BRACES:

$$s_{1,2} = \frac{-c l^2}{2 I_H} \pm \frac{1}{2}\sqrt{\left(\frac{c l^2}{I_H}\right)^2 - 4\left(\frac{k_1 + k_2 l^2}{I_H}\right)}$$

$$s_{1,2} = -s_A \pm s_B \; ; \; s_A = \frac{c l^2}{2 I_H} \qquad Eq\ (2)$$

$$s_B = \frac{1}{2 I_H}\sqrt{(c l^2)^2 - 4 I_H (k_1 + k_2 l^2)}$$

DEPENDING UPON THE VALUE OF s_B, THREE SEPARATE FORMS OF THE SOLUTION EXIST:

$(c l^2)^2 > 4 I_H (k_1 + k_2 l^2)$ $s_{1,2}$ ARE REAL

$(c l^2)^2 = 4 I_H (k_1 + k_2 l^2)$ $s_{1,2}$ ARE IDENTICAL

$(c l^2)^2 < 4 I_H (k_1 + k_2 l^2)$ $s_{1,2}$ ARE COMPLEX

EACH CASE WILL NOW BE SEPARATELY SOLVED.

Title REAL ROOT CASE
Prepared by R.T. Hailey Date 4/24/64
Checked by ______ Date ______

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

Report No. ST 503.04 Page ___
Project MARINER C
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$$F(s) = \frac{\dot{\theta}_0}{(s-s_1)(s-s_2)} + \frac{q}{I_H s(s-s_1)(s-s_2)}$$

USING THE METHOD OF PARTIAL FRACTIONS

$$F(s) = \frac{\frac{q}{I_H s_1 s_2}}{s} + \frac{\left[\frac{q+\dot{\theta}_0 I_H s_1}{I_H s_1(s_1-s_2)}\right]}{(s-s_1)} - \frac{\left[\frac{q+\dot{\theta}_0 I_H s_2}{I_H s_2(s_1-s_2)}\right]}{(s-s_2)} \qquad Eq(3)$$

PERFORMING THE INVERSE LA PLACE TRANSFORM:

$$\theta = \frac{q}{I_H s_1 s_2} + \left[\frac{q+\dot{\theta}_0 I_H s_1}{I_H s_1(s_1-s_2)}\right] e^{s_1 t} - \left[\frac{q+\dot{\theta}_0 I_H s_2}{I_H s_2(s_1-s_2)}\right] e^{s_2 t}$$

FOR $\theta = \theta_{MAX}$ SET $\dot{\theta} = 0$: $\qquad Eq(4)$

$$\dot{\theta} = \left[\frac{q+\dot{\theta}_0 I_H s_1}{I_H (s_1-s_2)}\right] e^{s_1 t} - \left[\frac{q+\dot{\theta}_0 I_H s_2}{I_H (s_1-s_2)}\right] e^{s_2 t} = 0$$

$$t_1 = \ln\left[\frac{q+\dot{\theta}_0 I_H s_2}{q+\dot{\theta}_0 I_H s_1}\right]^{\left(\frac{1}{s_1-s_2}\right)} \qquad Eq(5)$$

SUBSTITUTING Eq(5) IN Eq(4):

$$\boxed{\begin{aligned}\theta_{MAX} = \frac{q}{I_H s_1 s_2} &+ \left[\frac{q+\dot{\theta}_0 I_H s_1}{I_H s_1(s_1-s_2)}\right]\left[\frac{q+\dot{\theta}_0 I_H s_2}{q+\dot{\theta}_0 I_H s_1}\right]^{\left(\frac{s_1}{s_1-s_2}\right)} \\ &- \left[\frac{q+\dot{\theta}_0 I_H s_2}{I_H s_2(s_1-s_2)}\right]\left[\frac{q+\dot{\theta}_0 I_H s_2}{q+\dot{\theta}_0 I_H s_1}\right]^{\left(\frac{s_2}{s_1-s_2}\right)}\end{aligned}}$$

REAL ROOT CASE Eq(6)

FOR MAXIMUM ACCELERATION: SET $\dddot{\theta} = 0$

$$\ddot{\theta} = s_1\left[\frac{q+\dot{\theta}_0 I_H s_1}{I_H (s_1-s_2)}\right] e^{s_1 t} - s_2\left[\frac{q+\dot{\theta}_0 I_H s_2}{I_H (s_1-s_2)}\right] e^{s_2 t}$$

$$\dddot{\theta} = s_1^2[\ ]e^{s_1 t} - s_2^2[\ ]e^{s_2 t} = 0; \quad t_2 = \ln\left\{\left[\frac{q+\dot{\theta}_0 I_H s_2}{q+\dot{\theta}_0 I_H s_1}\right]\left(\frac{s_2}{s_1}\right)^2\right\}$$

$$\begin{aligned}\ddot{\theta}_{MAX} = s_1&\left[\frac{q+\dot{\theta}_0 I_H s_1}{I_H (s_1-s_2)}\right]\left\{\left[\frac{q+\dot{\theta}_0 I_H s_2}{q+\dot{\theta}_0 I_H s_1}\right]\left(\frac{s_2}{s_1}\right)^2\right\}^{\left(\frac{s_1}{s_1-s_2}\right)} \\ - s_2&\left[\frac{q+\dot{\theta}_0 I_H s_2}{I_H (s_1-s_2)}\right]\left\{\left[\frac{q+\dot{\theta}_0 I_H s_2}{q+\dot{\theta}_0 I_H s_1}\right]\left(\frac{s_2}{s_1}\right)^2\right\}^{\left(\frac{s_2}{s_1-s_2}\right)}\end{aligned}$$

REAL ROOT CASE Eq(7)

Title COMPLEX ROOT CASE		JET PROPULSION LABORATORY CALIFORNIA INSTITUTE OF TECHNOLOGY	Report No. ST 50204 Page
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Checked by	Date		Classification UNCLASS

$$F(s) = \frac{\dot{\theta}_0}{(s+s_A)^2 + s_B^2} + \frac{q}{I_H s\left[(s+s_A)^2+s_B^2\right]} \quad ; \quad \begin{array}{l} s_1 = -s_A + i s_B \\ s_2 = -s_A - i s_B . \end{array}$$

TAKING THE INVERSE LAPLACE TRANSFORM:

$$\theta = \left(\frac{\dot{\theta}_0}{s_B}\right)\left[e^{-s_A t}\sin s_B t\right] + \left(\frac{q}{I_H s_B}\right)\int_0^t \left[e^{-s_A t}\sin s_B t\right]dt$$

$$= \left(\frac{\dot{\theta}_0}{s_B}\right)\left[e^{-s_A t}\sin s_B t\right] + \frac{q}{I_H s_B(s_A^2+s_B^2)}\left[s_B - e^{-s_A t}(s_A \sin s_B t + s_B \cos s_B t)\right]$$

$$\boxed{\theta = q'(1-e^{-s_A t_3}\cos s_B t_3) + \left(\frac{\dot{\theta}_0 - q' s_A}{s_B}\right) e^{-s_A t_3}\sin s_B t_3 \qquad \text{WHERE: } q' = q/I_H(s_A^2+s_B^2) \qquad \underline{\text{COMPLEX ROOT CASE}} \quad Eq\ (8)}$$

FOR θ_{MAX}, FIND t_3 @ $\dot{\theta} = 0$:

$$\dot{\theta} = -q' e^{-s_A t}(-s_B \sin s_B t) - q'(-s_A e^{-s_A t})\cos s_B t + \left(\frac{\dot{\theta}_0 - q' s_A}{s_B}\right)\left[e^{-s_A t}(s_B \cos s_B t) + (-s_A e^{-s_A t}\sin s_B t)\right]$$

$$\dot{\theta} = e^{-s_A t}\left[a \sin s_B t + b \cos s_B t\right] = 0$$

$$a = q' s_B - s_A\left(\frac{\dot{\theta}_0 - q' s_A}{s_B}\right)$$

$$b = q' s_A + s_B\left(\frac{\dot{\theta}_0 - q' s_A}{s_B}\right)$$

$$t_3 = \frac{1}{s_B}\tan^{-1}\left(\frac{b}{a}\right) = \boxed{\frac{1}{s_B}\tan^{-1}\left[\frac{s_B \dot{\theta}_0}{s_A \dot{\theta}_0 - q/I_H}\right] = t_3 \qquad Eq\ (9)}$$

<u>COMPLEX ROOT CASE</u>

FOR MAXIMUM ACCELERATION: $\dddot{\theta} = 0$

$$\ddot{\theta} = e^{-s_A t}\left\{\underbrace{(a s_B - b s_A)}_{b'}\cos s_B t + \underbrace{(-b s_B - a s_A)}_{a'}\sin s_B t\right\}$$

$$\dddot{\theta} = e^{-s_A t}\left\{(a' s_B - b' s_A)\cos s_B t + (-b' s_B - a' s_A)\sin s_B t\right\} = 0$$

EQUATING THE TERM IN THE CURLY BRACKETS TO ZERO:

$$t_4 = \frac{1}{S_B} \tan^{-1}\left[\frac{a' S_B - b' S_A}{b' S_B + a' S_A}\right]$$

$$t_4 = \frac{1}{S_B} \tan^{-1}\left\{\frac{\dot{\theta}_0 (3S_A^2 - S_B^2) - 2S_A\, g/I_H}{\frac{\dot{\theta}_0 S_A}{S_B}(S_A^2 - 3S_B^2) + \frac{g}{I_H S_B}(S_B^2 - S_A^2)}\right\} \qquad Eq\,(10)$$

$$\ddot{\theta}_{MAX} = e^{-S_A t_4}\left\{\left(\frac{g}{I_H} - 2S_A \dot{\theta}_0\right)\cos S_B t_4 + \left[\frac{\dot{\theta}_0}{S_B}(S_A^2 - S_B^2) - \frac{g S_A}{I_H S_B}\right]\sin S_B t_4\right\}$$

COMPLEX ROOT CASE Eq (11)

IDENTICAL ROOT CASE: $s_1 = s_2 = -S_A$

$$F(s) = \frac{\dot{\theta}_0}{(s+S_A)^2} + \frac{g/I_H}{s(s+S_A)^2}$$

TAKING THE INVERSE LAPLACE TRANSFORM:

$$\theta = \dot{\theta}_0 t_5 e^{-S_A t_5} + \frac{g}{I_H S_A}\left[\frac{1}{S_A} - e^{-S_A t_5}\left(t_5 + \frac{1}{S_A}\right)\right]$$

$$\theta_{MAX} = \frac{1}{I_H S_A^2}\left\{g + e^{-S_A t_5}\left[t_5 \dot{\theta}_0 I_H S_A^2 - g(S_A t_5 + 1)\right]\right\}$$

IDENTICAL ROOT CASE Eq (12)

FOR θ_{MAX}, $\dot{\theta} = 0$

$$\dot{\theta} = \frac{e^{-S_A t_5}}{I_H S_A^2}\left\{-S_A^3 t_5 \dot{\theta}_0 I_H + g S_A^2 t_5 + \cancel{g S_A} + \dot{\theta}_0 I_H S_A^2 - \cancel{g S_A}\right\} = 0$$

$$t_5 = \frac{\dot{\theta}_0 I_H}{S_A \dot{\theta}_0 I_H - g} \qquad Eq\,(13)$$

Title IDENTICAL ROOT CASE
Prepared by R.T. Hailey Date 4/24/64
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FOR MAXIMUM ACCELERATION:

$$\ddot{\theta} = \frac{-s_A e^{-s_A t_6}}{I_H}\left[-s_A t_6 \dot{\theta}_0 I_H + q t_6 + \dot{\theta}_0 I_H\right] + \frac{e^{-s_A t_6}}{I_H}\left[-s_A \dot{\theta}_0 I_H + q\right]$$

$$\boxed{\ddot{\theta}_{MAX} = e^{-s_A t_6}\left\{(t_6 s_A - 1)(s_A \dot{\theta}_0 - q/I_H) - s_A \dot{\theta}_0\right\}}$$

IDENTICAL ROOT CASE Eq (14)

$$\dddot{\theta} = e^{-s_A t_6}\left\{s_A(s_A\dot{\theta} - q/I_H) - s_A\left[(t s_A - 1)(s_A\dot{\theta}_0 - q/I_H) - s_A\dot{\theta}_0\right]\right\} = 0$$

$$\boxed{t_6 = \frac{3 s_A \dot{\theta}_0 I_H - 2q}{s_A(s_A \dot{\theta}_0 I_H - q)}} \qquad \text{Eq (15)}$$

INITIAL DECELERATION: RETURNING TO THE D.E. ON p B2

$$\ddot{\theta} = \frac{q}{I_H} - \frac{c\ell^2}{I_H}\dot{\theta} - \frac{(k_1 + k_2\ell^2)}{I_H}\theta$$

AT $t = 0$ $\theta = 0$

$$\boxed{\ddot{\theta}_I = \frac{q}{I_H} - \frac{c\ell^2}{I_H}\dot{\theta}_0} \qquad \text{Eq (16)}$$

DEPLOYMENT TIME

$$I_H \ddot{\theta} + K\theta = T_0 \quad ; \quad k = \begin{cases} 6/\pi & \text{FOR 2 SPRING} \\ 3/\pi & \text{FOR 1 SPRING} \end{cases} \quad ; \quad \omega^2 = \frac{k}{I_H}$$

$$\theta_0 = \dot{\theta}_0 = 0$$

$$\theta = \frac{T_0}{K}\left[1 - \cos\omega t\right]$$

AT $\theta = \pi/2$:

$$\boxed{t = \sqrt{\frac{I_H}{k}} \cos^{-1}\left[1 - \frac{\pi k}{2T_0}\right]} \qquad \text{Eq (17)}$$

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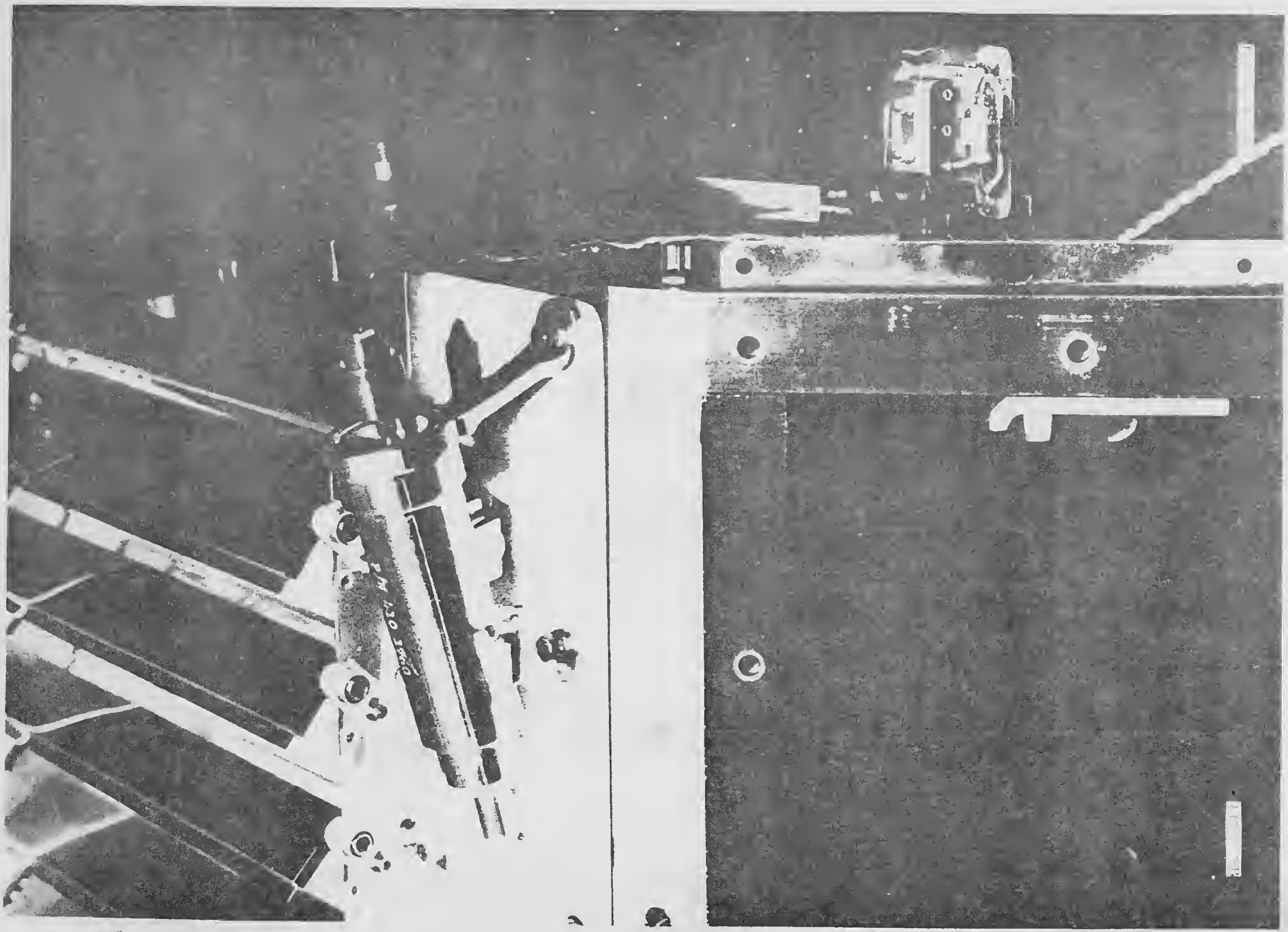
HINGE INERTIA= 138.250INLB-SEC2 FRICTION= .000
TORQUE= 15.000IN-LB DEGREES PRELOAD= 540.000

DEPLOY VELOCITY= .5589RD/SEC TIME= 5.458SEC

DAMPING RATIO	DISPLACEMENTS FOR ACTUAL AND NOMINAL CRUISE DAMPER SPRINGS=509/530LB/IN			
	PANEL ANGULAR DISPL (DEGREES)		DAMPER DISPL (INCHES)	
	ACTUAL	NOMINAL	ACTUAL	NOMINAL
.00	3.0814	3.0189	.2958	.2897
.05	2.8546	2.7967	.2740	.2684
.10	2.6564	2.6025	.2550	.2498
.15	2.4819	2.4315	.2382	.2334
.20	2.3272	2.2800	.2234	.2188
.25	2.1894	2.1450	.2101	.2059
.30	2.0659	2.0240	.1983	.1942
.35	1.9546	1.9150	.1876	.1838
.40	1.8539	1.8163	.1779	.1743
.45	1.7625	1.7267	.1691	.1657
.50	1.6790	1.6450	.1611	.1579
.55	1.6027	1.5702	.1538	.1507
.60	1.5326	1.5015	.1471	.1441
.65	1.4680	1.4383	.1409	.1380
.70	1.4083	1.3798	.1351	.1324
.75	1.3531	1.3257	.1298	.1272
.80	1.3018	1.2754	.1249	.1224
.85	1.2540	1.2286	.1203	.1179
.90	1.2094	1.1850	.1161	.1137
.95	1.1678	1.1441	.1121	.1098
1.00	1.1287	1.1059	.1083	.1061

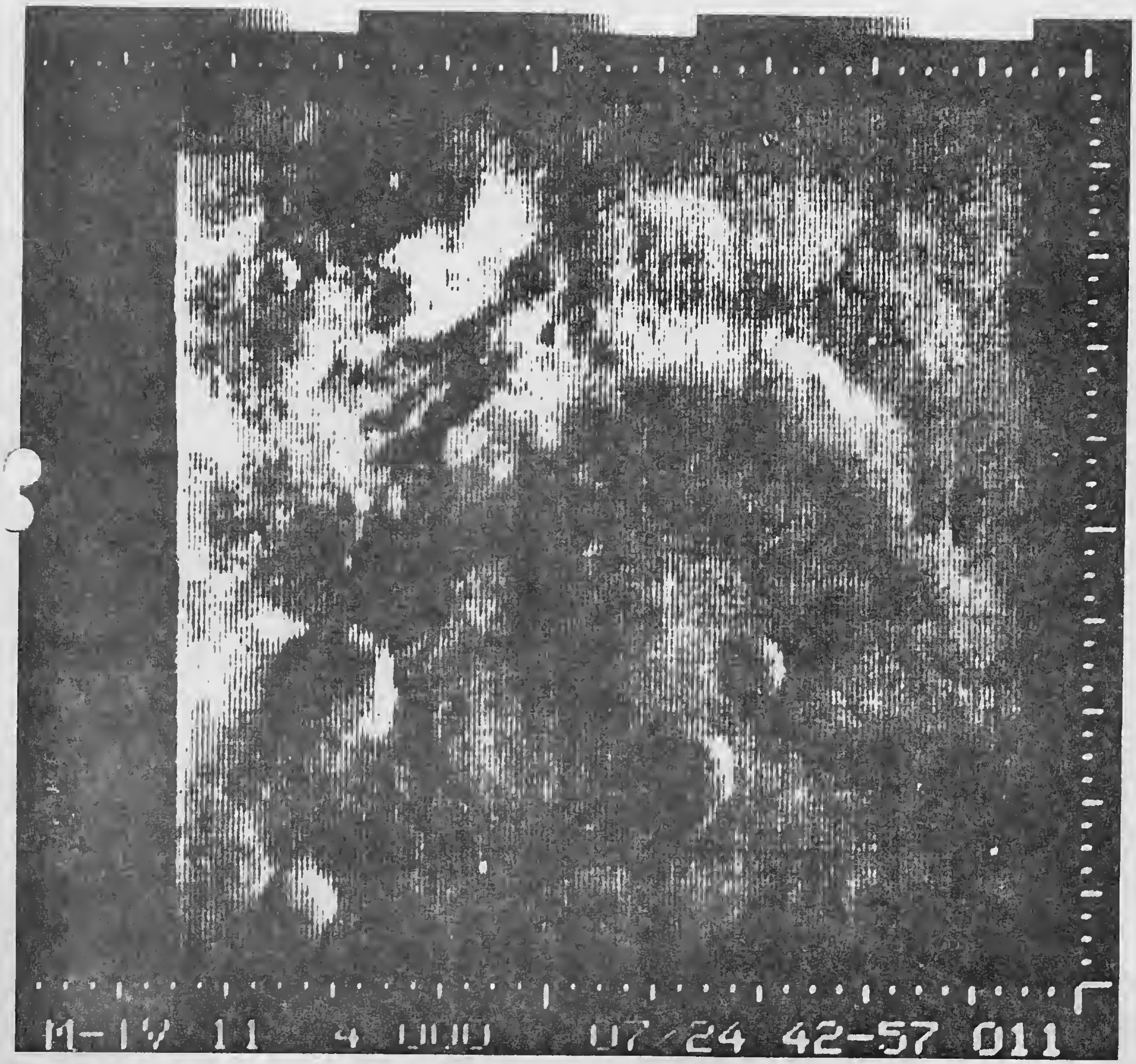
TYPICAL COMPUTER PRINTOUT FOR FREE-FALL ANALYSIS



Installed [illegible] Damper

Exhibit B-6

ECL 89B



Photograph, Martian Surface